

Kuroshio Transport East of Taiwan and the Effect of Mesoscale Eddies

Magdalena Andres

Wood Hole Oceanographic Institution
266 Woods Hole Road
Woods Hole, MA 02543

phone: (508) 289-2660 fax: (508) 457-2181 email: mandres@whoi.edu

Award Number: N00014-12-1-0445
<http://kirin.apl.washington.edu/okmc/>

LONG-TERM GOALS

The long-term goal of this project is to improve understanding and predictability of the regional circulation in the western North Pacific.

OBJECTIVES

The objective of this project is to characterize variability in the Kuroshio east of Taiwan and to understand (1) how this variability is related to variability in the upstream region, where the North Equatorial Current bifurcates forming the northward-flowing Kuroshio and the southward-flowing Mindanao Current and (2) how westward-propagating mesoscale eddies that arrive east of Taiwan from the ocean interior affect Kuroshio variability. This will establish the advective versus the eddy-driven contributions to Kuroshio variability east of Taiwan.

Specific goals are as follows:

- 1.) Measure the time series of Kuroshio full water column absolute geostrophic transport and velocity structure east of Taiwan for a minimum of 12 months beginning August 2012.
- 2.) Characterize the time variability of this transport and velocity structure at periods ranging from 2 days to 1-year.
- 3.) Relate this variability to forcing using NCEP and/or ECMWF wind products.
- 4.) Put variability at the KTV1-line into a regional context by comparing the observations with other contemporaneous data sets.
- 5.) Characterize long-term variability by comparing measurements from this experiment with observations from previous experiments.

APPROACH

To determine the time-varying Kuroshio transport and velocity structure east of Taiwan, in situ measurements were collected with moorings deployed for 2 years. This work was carried out as a collaboration between M. Andres at the Woods Hole Oceanographic Institution (WHOI) and Drs. S.

Jan and M.-H. Chang from the National Taiwan University (NTU), whose companion projects were funded by the Taiwanese National Science Council (now the Ministry of Science and Technology, MOST).

The field work was carried out along the Yaeyama Ridge (**Figure 1**) which is about 100 km south of the Ilan Ridge, which separates the Philippine Basin from the East China Sea. The field experiment included shipboard and time series measurements. Moorings were deployed in November 2012 and recovered in November 2014 to provide 2-year long time series. On the intervening cruises, hydrographic data were collected and interim data from the moorings were downloaded via telemetry. Cruises were conducted on Taiwanese research vessels, primarily the R/V Ocean Researcher 1 (OR1).

Instruments were deployed on the KTV1-line (along the Yaeyama Ridge) and along a meridional section that stretches southward from the KTV-1 line. The array included 6 bottom-moored pressure-sensor-equipped inverted echo sounders (PIESs) one of which had an added current-sensor (CPIES). Three of the PIESs are owned by NTU (Jan); two PIESs and the CPIES are owned by WHOI (Andres). Making concurrent measurements were 3 tall moorings (Chang, NTU) deployed along KTV-1. Each tall mooring was instrumented with an upward-looking ADCP at ~500 m depth and a deep RCM-8 current sensor (**Figure 2**). This combination of instruments provided excellent horizontal and temporal resolution of the Kuroshio's time-varying position (including resolving a double-core structure when it is present) and allows us to determine the full-water column transport time series without having to assume a level of no motion.

WORK COMPLETED

Training and instrument deployment/recovery

The PIESs and CPIES were built by the University of Rhode Island. The NTU instruments (3 PIESs) and WHOI instruments (2 PIESs, 1 CPIES) were shipped to Taiwan. Andres and an engineer from the University of Rhode Island traveled to Taipei, Taiwan to provide PIES training for our NTU collaborators and technicians. PIESs were deployed from the OR1 in November 2012 and a telemetry cruise in June 2013 retrieved 8 months of processed data from the PIESs/CPIES. Several subsequent telemetry (and hydrography) cruises were carried out. The instruments were recovered from the OR1 in November 2014. Data recovery was excellent and complete, except for the time series from the on-shore most PIES belonging to our NTU colleagues; at this site only telemetry data are available for the first year as the instrument could not be recovered, likely due to a soft bottom and shifted sands, possibly because of earthquake activity in the region. In total, 9 cruises were conducted. The shipboard data from these cruises, including lowered ADCP measurements, have been reported by Jan et al., (2015).

Data processing – acoustic travel time

In preparation for the field program, V. Mensah, a Ph.D. student from NTU advised by Jan, visited WHOI for two weeks in March 2012. Andres trained Mensah in the interpretation of acoustic-travel-time data collected by PIESs. Using historical hydrography from the region, gravest empirical mode (GEM) lookup tables were constructed. These relate synthetic acoustic travel time, calculated from an equation for the speed of sound in seawater (Del Grosso, 1974), to vertical profiles of temperature, salinity and density (Meinen, 2001). After instrument recovery (fall 2014), the lookup tables were used with the measured acoustic-travel-time time series to reconstruct time-varying profiles of specific volume anomaly at each PIESs (or CPIES) site. These have been used to construct time series of the

baroclinic velocities and transports (referenced to 1200 m) across the Kuroshio east of Taiwan and across the meridional line extending southward from the Yaeyama Ridge.

Data processing – leveling pressure sensors

In order to reference the baroclinic velocities and transports determined from the acoustic-travel times so that absolute geostrophic velocities and transports can be calculated, the pressure sensors on the PIESs (or CPIES) are used to obtain the time-varying reference velocities. In order to do this, the instruments must be “leveled” (see Donohue et al., 2010 for a description of the methodology). A new technique to do this by capitalizing on the upward looking ADCPs in the array was developed through this project. We established and verified this technique with data from a companion OKMC project (Lien et al., 2014), **Figure 3**. For the PIESs/CPIES east of Taiwan, the ADCP data collected by Chang (in a separately-funded Taiwanese project) are being used to level our PIESs/CPIES instruments in order to obtain time series of absolute geostrophic velocities in the region. This work is ongoing.

Presentations and publications

Results from the project east of Taiwan were presented at an invited talk at the 2015 Pacific Asian Marginal Seas Meeting (Andres and Jan, “The structure and variability of the Kuroshio east of Taiwan inferred from an array of pressure-sensor equipped inverted echo sounders”) and in a poster at the meeting (Tsai, “Impact of SSH anomalies on PIES data east of Taiwan and Luzon”). In addition results have been presented by Andres at the yearly Origins of the Kuroshio and Mindanao Currents PI meeting.

Results from this program will be published in peer-reviewed journals with one paper about the interaction of mesoscale eddies with the Kuroshio east of Taiwan and Luzon nearly ready for submission: C.-J. Tsai, M. Andres, S. Jan, V. Mensah, T. Sanford, R.-C. Lien, and C. Lee, Fate of sea surface height anomalies that impinge on the Kuroshio east of Taiwan and northeast of Luzon, to be submitted to the *Journal of Geophysical Research*. A second manuscript, about the methodologies developed here to use glider data for PIES calibration and ADCP data for PIES leveling, is under preparation. Further, the results from this study will be included in several publications in an upcoming Oceanography special issue including one lead by Andres, which is currently under preparation.

RESULTS

The analysis of historical hydrography established that acoustic-travel-time can be used as a proxy for the vertical profiles of specific volume anomaly and temperature in the region east of Taiwan. The GEM lookup tables constructed from these data are critical for making use of acoustic travel time data to calculate vertical velocity shear. This has enabled calculation of a time series of the Kuroshio’s absolute geostrophic velocity along the KTV-1 line (Donohue et al., 2010). Furthermore, the data processing and analyses from this study have demonstrated that hydrographic data collected by gliders flying through the PIESs/CPIES array are particularly useful to calculate the GEM lookup table.

Comparison of acoustic-travel-time with concurrent satellite altimetry suggests that the instruments are capturing changes in the sub-surface structure of the Kuroshio that arises due to the impact of mesoscale eddies that propagate into the region from the ocean interior (**Figure 4**). Qualitative results suggest that cyclonic eddies lead to a more barotropic (less vertical shear) Kuroshio by elevating the offshore edge of the pycnocline and depressing the on-shore edge of the pycnocline across the Kuroshio. A first draft of a paper about this has been written with one of Jan’s Masters Degree students as lead-author. This will be submitted shortly to the *Journal of Geophysical Research*.

The analysis of data from the companion study of the Kuroshio east of Luzon has resulted in mean baroclinic and absolute velocity sections for the current there (*Figure 5*). Similar analysis is ongoing for the Kuroshio east of Taiwan. Furthermore, comparison between the time series of Kuroshio strength and velocity structure east of Luzon and east of Taiwan indicates that much of the variability is due to the local arrival of eddies from the ocean interior.

IMPACT FOR SCIENCE

Understanding the variability of the Kuroshio east of Taiwan has implications for predictability in the downstream region where the Kuroshio sometimes intrudes onto the East China Sea shelf northeast of Taiwan. There is evidence that a weak Kuroshio corresponds with strong intrusions of the Kuroshio onto the East China Sea shelf (Gawarkiewicz et al., 2011). Understanding the Kuroshio interactions with the continental shelf is very important for forecasting acoustic propagation conditions in this region (Lermusiaux et al., 2011).

Determining the advective versus the eddy-driven contributions to Kuroshio variability east of Taiwan is relevant to understanding acoustic propagation in the Philippine Sea. Furthermore, this is an area where typhoons frequently pass, and the data collected here should provide some very interesting case studies for determining how the Kuroshio reacts to the passage of typhoons.

RELATIONSHIP TO OTHER PROGRAMS

This project is part of the Origins of the Kuroshio and Mindanao Currents (OKMC) program (<http://kirin.apl.washington.edu/okmc/>), funded by the Office of Naval Research and the Observations of Kuroshio Transports and Variabilities (OKTV) program (*Figure 6*), funded by the Taiwanese National Science Council. Instrumentation along the KTV-1 line is funded in part by this ONR proposal and in part by the OKTV program (Sen Jan, PI). Ship time for instrument deployments and recoveries was provided through OKTV. Training for PIES deployments and recoveries was provided through this proposal. Data processing and analysis were carried out collaboratively between NTU and WHOI. The results from this program are being built upon through the Taiwanese Study of the Kuroshio II (SK-II) program.

REFERENCES

- Del Grosso, V. A., 1974. New equation for the speed of sound in natural waters (with comparisons to other equations). *J. Acoust. Soc. Am.*, **56**(4), 1084-1091.
- Donohue, K. A., D. R. Watts, K. L. Tracey, A. D. Greene and M. Kennelly, 2010. Mapping circulation in the Kuroshio Extension with an array of Current and Pressure recording Inverted Echo Sounders. *Journal of Atmospheric Oceanic Technology*, doi:10.1175/2009JTECHO686.1.
- Gawarkiewicz, G., S. Jan, P.F.J. Lermusiaux, J.L. McClean, L. Centurioni, K. Taylor, B. Cornuelle, T.F. Duda, J. Wang, Y.J. Yang, T. Sanford, R.-C. Lien, C. Lee, M.-A. Lee, W. Leslie, P.J. Haley Jr., P.P. Niiler, G. Gopalakrishnan, P. Velez-Belchi, D.-K. Lee, and Y.Y. Kim, 2011. Circulation and intrusions northeast of Taiwan: Chasing and predicting uncertainty in the cold dome, *Oceanography*, **24**(4):110–121, <http://dx.doi.org/10.5670/oceanog.2011.99>.

- Jan, S., Y.J. Yang, J. Wang, V. Mensah, T.-H. Kuo, M.-D. Chiou, C.-S. Chern, M.-H. Chang, and H. Chien, 2015. Large variability of the Kuroshio at 23.75°N east of Taiwan, *J. Geophys. Res. Oceans*, **120**, 1825–1840, doi:10.1002/2014JC010614.
- Lermusiaux, P.F.J., J. Xu, C.F. Chen, S. Jan, L.Y. Chiu, and Y.-J. Yang, 2010. Coupled ocean-acoustic prediction of transmission loss in a continental shelfbreak region: Predictive skill, uncertainty quantification and dynamical sensitivities. *IEEE Journal of Oceanic Engineering*, **35**:895–916, <http://dx.doi.org/10.1109/JOE.2010.2068611>.
- Lien, R.-C., B. Ma, Y.-H. Cheng, C.-R. Ho, B. Qiu, C. M. Lee, and M.-H. Chang, 2014. Modulation of Kuroshio transport by mesoscale eddies at the Luzon Strait entrance, *J. Geophys. Res. Oceans*, **119**, 2129–2142, doi:10.1002/2013JC009548.
- Meinen, C.S., 2001. Structure of the North Atlantic Current in stream-coordinates and the circulation in the Newfoundland Basin. *Deep Sea Res.*, **48**(7), 1553– 1580, doi:10.1016/S0967-0637(00)00103-5.

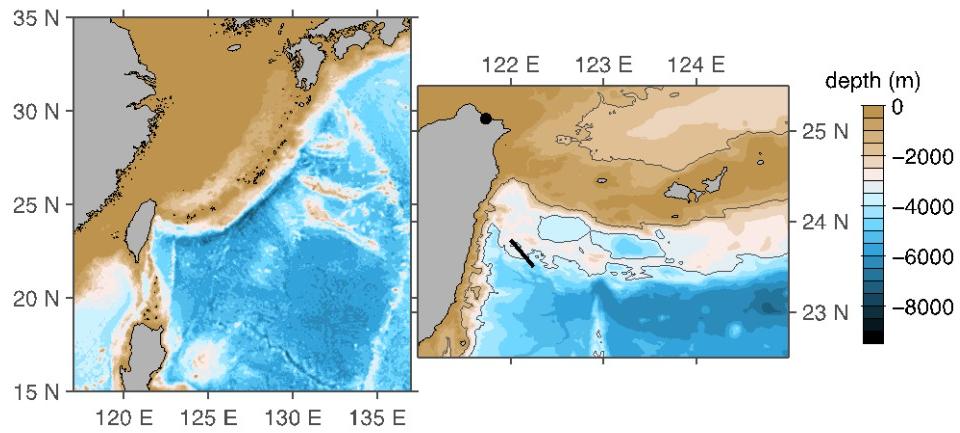


Figure 1. Map of the western North Pacific. Grey contours in the right panel show the 3500 m and 1500 m isobaths.

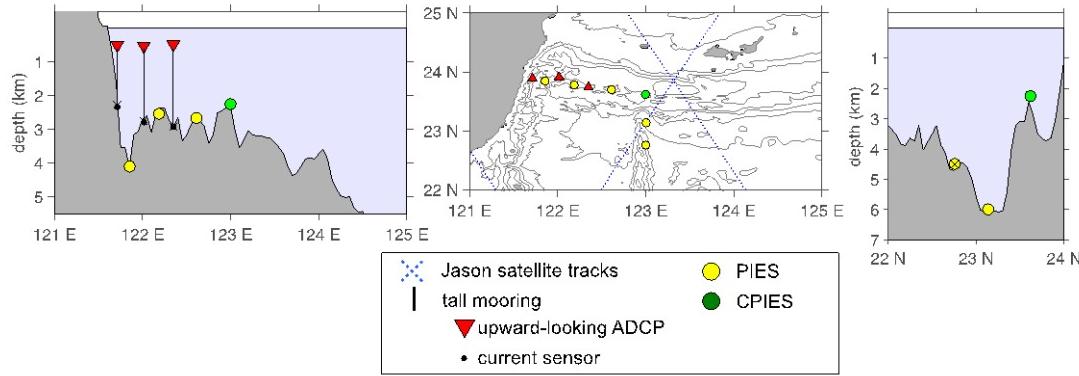


Figure 2. Map and cross-sections showing the instrumentation east of Taiwan.

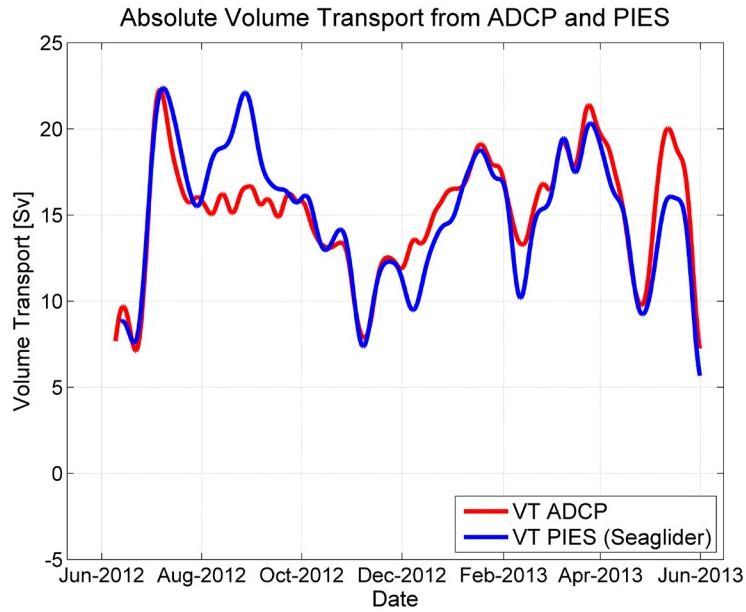


Figure 3. Verification of the new ADCP “leveling” method for an array of PIEs east of Luzon. The lines show the absolute geostrophic volume transport in the Kuroshio east of Luzon calculated from ADCPs (red) and from PIEs leveled according to the new methodology (blue).

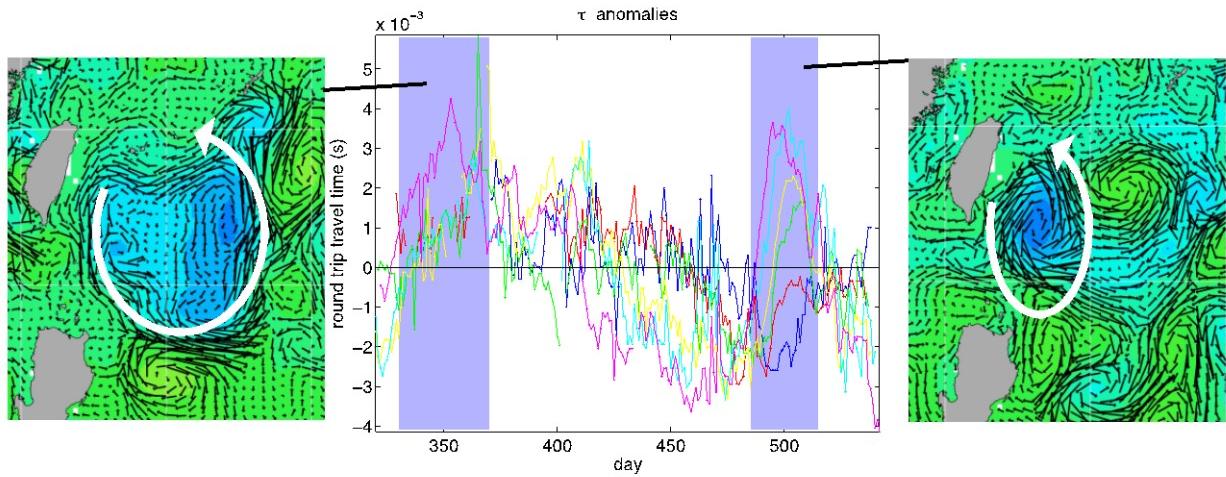


Figure 4. Time series of acoustic-travel-time (means removed) retrieved from the CPIES/PIEs in June 2013 via acoustic telemetry. Highlighted periods show times when acoustic-travel times are anomalously long due to a shallower than average thermocline. These times correspond to arrivals of cyclonic eddies (sea surface lows).

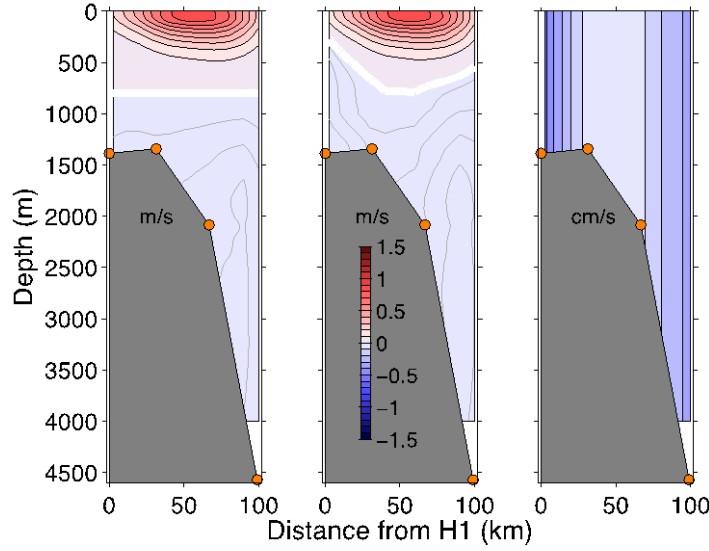


Figure 5. 12-month means of the baroclinic velocity (left, from acoustic travel time), absolute velocity (center, sum of the left and right panels) and reference velocity (from leveled pressure gages) for the Kuroshio east of Luzon. These were determined from PIESs that were leveled with neighboring ADCP data. This methodology (developed by us through this project) is presently being applied to the measurements east of Taiwan.

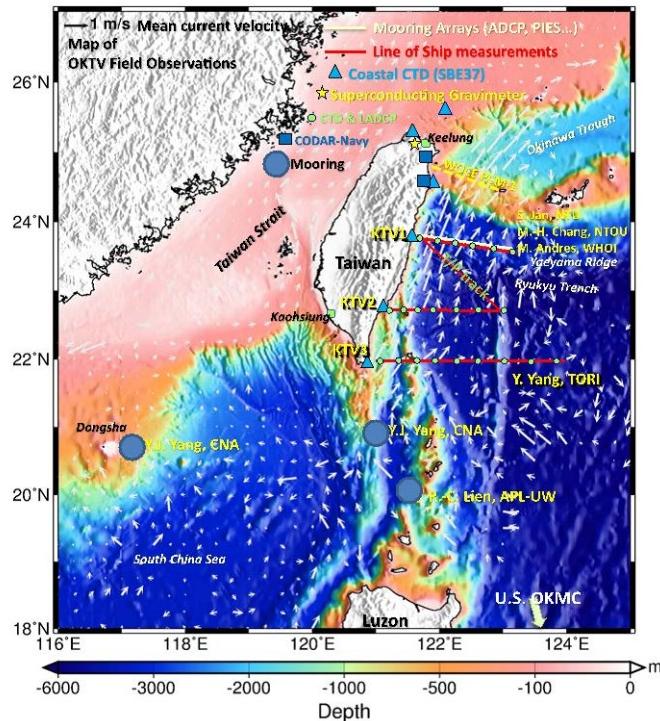


Figure 6. Map summarizing the elements of the Taiwanese OKTV field program. The ONR-funded efforts described in this annual report complement the OKTV measurements near the KTV1-line.
(Figure courtesy of Sen Jan.)